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# REVOLUTIONIZING OUR VIEW OF PROTOSTELLAR MULTIPLICITY AND DISKS: THE VLA NASCENT DISK AND MULTIPLICITY (VANDAM) SURVEY OF THE PERSEUS MOLECULAR CLOUD

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**Abstract.** There is substantial evidence for disk formation taking place during the early stages of star formation and for most stars being born in multiple systems; however, protostellar multiplicity and disk searches have been hampered by low resolution, sample bias, and variable sensitivity. We have conducted an unbiased, high-sensitivity Karl G. Jansky Very Large Array (VLA) survey toward all known protostars ( $n = 94$ ) in the Perseus molecular cloud ( $d \sim 230$  pc), with a resolution of  $\sim 15$  AU ( $0.06''$ ) at  $\lambda = 8$  mm. We have detected candidate protostellar disks toward 17 sources (with 12 of those in the Class 0 stage) and we have found substructure on  $< 50$  AU scales for three Class 0 disk candidates, possibly evidence for disk fragmentation. We have discovered 16 new multiple systems (or new components) in this survey; the new systems have separations  $< 500$  AU and 3 by  $< 30$  AU. We also found a bi-modal distribution of separations, with peaks at  $\sim 75$  AU and  $\sim 3000$  AU, suggestive of formation through two distinct mechanisms: disk and turbulent fragmentation. The results from this survey demonstrate the necessity and utility of uniform, unbiased surveys of protostellar systems at millimeter and centimeter wavelengths.

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## 1 Introduction

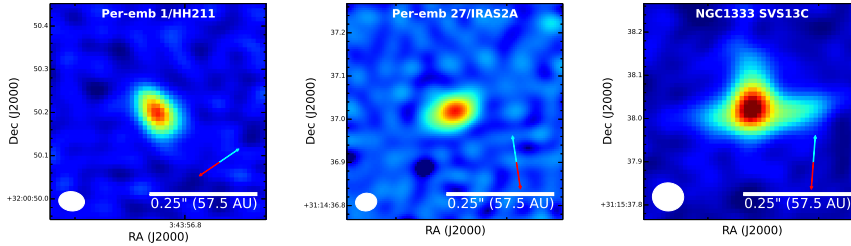
Stars form due to the gravitational collapse of dense cores within molecular clouds. Conservation of angular momentum in this infalling material causes the formation of a rotationally-supported disk around the nascent protostar. However, this picture may be complicated by the presence of magnetic fields that can remove angular momentum from the infalling material (Allen et al. 2003). In a similar vein, wide multiple protostellar systems can form via rotational breakup of the collapsing cloud (e.g., Burkert and Bodenheimer 1993). Turbulent fragmentation (Padoan et al. 2007) has recently become a favorable route for the formation of both wide and close multiples; the close multiples migrate inward from initially larger separations (e.g., Offner et al. 2010). Close multiples may also form by fragmentation of a massive disk via gravitational instability (e.g., Adams et al. 1989); however, it is unknown if disks of sufficient mass and radius form in young protostellar systems.

Thus far, sub/millimeter studies of Class 0 protostars have not had the resolution to resolve the scale of disks and close multiples, and most samples have been small and/or biased. To make a substantial leap in our knowledge of both protostellar disks and multiplicity, we have conducted the VLA Nascent Disk and Multiplicity (VANDAM) Survey toward all known protostars in the Perseus molecular cloud. The survey was conducted in A and B configurations with the VLA at 8 mm, 1 cm, 4 cm, and 6.4 cm, observed only in wide-band continuum and reaching a high spatial resolution of  $0''.065$  (15 AU) at 8 mm. We will focus only on the 8 mm and 1 cm results in this contribution. Our sample is drawn primarily from the *Spitzer* survey by Enoch et al. (2009) as well as all known candidate first hydrostatic core objects and other deeply embedded sources.

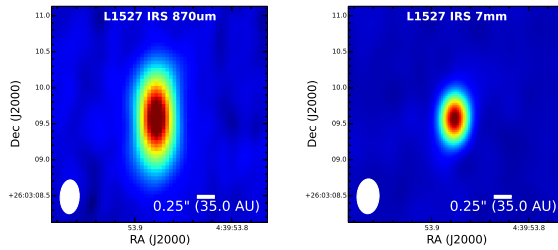
## 2 Protostellar Disks

We have detected resolved structures that are consistent with protostellar disks toward 12/43 Class 0 sources and 5/37 Class I sources. Examples of a few Class 0 disk candidates are shown in Figure 1. Some of the other candidates are further analyzed in Segura-Cox et al. (submitted) and the apparent circumbinary disk candidates are shown in Tobin et al. (submitted). Of the candidates shown, they appear to have radii of 30 AU or less. To determine if we are tracing the full extent of the disks at 8 mm, we examined both ALMA 870  $\mu\text{m}$  data and VLA 7 mm data toward the known Class 0 disk around L1527 IRS (Tobin et al. 2012), shown in Figure 2. The 7 mm data from the VLA have a resolution of  $\sim 0''.25$ , but are convolved with the same restoring beam as the ALMA data; the 7 mm data recover all the flux observed in the most compact VLA configuration (Melis et al. 2011). The deconvolved sizes are  $0''.62$  and  $0''.26$  at 870  $\mu\text{m}$  and 7 mm, respectively, demonstrating that this disk has a smaller apparent radius at 7 mm. We have further verified the more compact 7 mm emission using visibility amplitude profiles. Thus, 8 mm disk sizes may be lower limits.

The smaller extents at longer wavelengths have been seen toward more-evolved



**Fig. 1.** VLA 8 mm images of selected disk candidates. The continuum emission from these sources is compact, but their extensions are perpendicular to the direction of the outflow, as expected for disks. The outflow directions are drawn in the lower right.

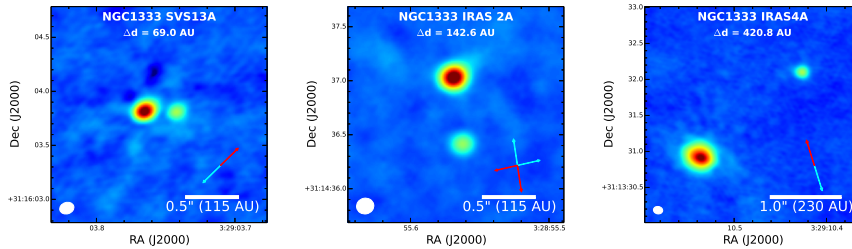


**Fig. 2.** Continuum images of L1527 from ALMA (left) at  $870\ \mu\text{m}$  and the VLA (right) at 7 mm from Tobin et al. (in prep.), convolved to the larger restoring beam in the ALMA image. The deconvolved sizes are  $0''.62$  and  $0''.26$  at  $870\ \mu\text{m}$  and 7 mm, respectively.

Class II objects (Pérez et al. 2012) and this is interpreted as the inward radial drift of the dust grains due to aerodynamic drag (Weidenschilling 1977). Models of dust growth and migration by Birnstiel et al. (2010) show that this effect may happen quickly enough to be apparent while still in the protostellar phase. We cannot, however, rule-out grain growth alone in the inner disk being responsible for this effect. Multi-wavelength modeling will be necessary to assess the difference in dust emission from short to long wavelengths.

### 3 Multiple Systems

With the ability to resolve multiples down to separations of 15 AU, the VANDAM survey represents a significant evolution in our knowledge of protostellar multiplicity. We show examples of a few multiples systems from the VANDAM survey in Figure 3. The companion of IRAS 2A, with a 142 AU separation, was first discovered in the VANDAM survey and is the apparent driving source of the east-west outflow from the system (Tobin et al. 2015a). The SVS13A multiple was first detected by Anglada et al. (2000) and IRAS 4A by Looney et al. (2000). Note that the brighter source in IRAS 4A (4A1 or SE) is well resolved at 8 mm,



**Fig. 3.** VLA 9 mm images of select multiple systems from the Perseus survey. The outflow direction(s) from the source(s) are plotted in the lower right corner.

possibly tracing a massive inner envelope or disk. From the 8 mm data, we have also detected linear polarization of the dust emission toward IRAS 4A1 (Cox et al. 2015), tracing an apparent toroidal magnetic field in this system.

The full multiplicity results of the VANDAM survey are shown in Tobin et al. (submitted), where we observe a clear bi-modal distribution of companion separations; one peak is at 75 AU and another is at  $\sim 3000$  AU. The 75 AU separation peak had not been previously detected due to limited resolution, and we suggest that the 75 AU peak may result from disk fragmentation. The 3000 AU separation peak may result from turbulent or Jeans fragmentation.

## 4 Summary

The key to the success of the VANDAM survey was in its unbiased nature and the superb sensitivity of the upgraded VLA, obtaining as complete a characterization of protostellar disks and multiple systems as possible.

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